Hidden Dark Matter at Neutrino Experiments

Jennifer Kile, Amarjit Soni

Brookhaven National Laboratory

September 9, 2009 DOE Review

Based on arXiv:0908.3892 [hep-ph]

Motivation

- Dark matter makes up $\sim 20\%$ of our universe.
- Recent interest in “hidden” models: low-mass particles connected to SM only via high-energy interactions–new particles don’t have to be heavy to be undiscovered.
- DM could be light, but coupled to SM particles at high scale.
- Little is known of nature of DM; should consider all observable DM-SM interactions.
- Desirable to do model-independent study of possible interactions of low-mass DM with SM.

Dark Matter Direct Searches

In usual DM direct search experiments:

- $O(10$ GeV $- 10$ TeV$)$ DM scatters elastically off $O(10 - 100$ GeV$)$ nucleus.
- DM nonrelativistic, $v_f \sim 10^{-3}c$. So, e.g. 100 GeV DM particle scattering off 100 GeV nucleus: nucleus receives momentum kick $p \sim 100$ MeV.

Instead, we consider:

- Inelastic scattering $fN \to FN'$ ($f =$ DM, $N, N' =$ nuclei, nucleons, $F = \nu, e$, BSM...)
- Take $m_F << m_f$: outgoing mom. p_F, $p_{N'} \sim m_f$.
- Use existing detectors to look for light, inelastically scattering DM?

Neutrino Experiments

- Can consider case where F is invisible (not done here) or visible. We take case $F = e$.

$$fN \rightarrow eN' \longrightarrow \text{NEUTRINO DETECTORS!}$$

- Existing solar & reactor experiments probe $O(1 - 100$ MeV$)$ range in E_ν for various nuclei.
  $\rightarrow$ corresponds to m_f of $1 - 100$ MeV.

- Will specifically look at Super-K:

  Usual interaction: $\bar{\nu}_e p \rightarrow n e^+ \; E_e \simeq E_\nu$.

  Replace ν with nonrelativistic f: $\bar{f} p \rightarrow n e^+ \; E_e \simeq m_f$.

  $\rightarrow$ f looks like monoenergetic neutrinos.
  $\rightarrow$ must translate limits on $\bar{\nu}_e$ to limits on $\bar{f}$.

Assumptions and Simplifications

Want model-independence–effective operator analysis.

Here, we consider DM which

- is fermionic *and*
- is a singlet under SM gauge group

So, we look for operators which

- are dimension-6 (or less)
- are $SU(3) \times SU(2) \times U(1)$-invariant
- can give the process $\bar{f}u \rightarrow de^{+}$ *and*
- aren't suppressed by ν mass.

Will find f is of the mass relevant to ν experiments.

Operator Basis

This leaves 6 operators (all 6-D, suppressed by C_I/Λ^2):

$$\begin{aligned}
\mathcal{O}_W &= g\bar{L}\tau^a\tilde{\phi}\sigma^{\mu\nu}fW^a_{\mu\nu} \\
\mathcal{O}_{\tilde{V}} &= \bar{\ell}_R\gamma_\mu f\phi^\dagger D_\mu\tilde{\phi} \\
\mathcal{O}_T &= \epsilon_{ij}\bar{L}^i\sigma^{\mu\nu}f\bar{Q}^j\sigma_{\mu\nu}d_R \\
\mathcal{O}_{Sd} &= \epsilon_{ij}\bar{L}^i f\bar{Q}^j d_R \\
\mathcal{O}_{Su} &= \bar{L}f\bar{u}_R Q \\
\mathcal{O}_{VR} &= \bar{\ell}_R\gamma_\mu f\bar{u}_R\gamma^\mu d_R
\end{aligned}$$

L, Q: $SU(2)$ doublets.
ℓ_R, u_R, d_R: right-handed $SU(2)$ singlets.
$\phi =$ SM Higgs, $\tilde{\phi} = i\tau^2\phi^*$.
In all cases, f right-handed.

Limits from DM Lifetime and γ's

- DM lifetime must be long, rarely decay to γ's ($\tau \gtrsim 10^{19}$yr) or e^+e^- ($\tau \gtrsim 10^{17}$yr):
  $\rightarrow$ New Physics scale $> 10^3$ TeV for 5 op's.
- One op less constrained: $\mathcal{O}_{VR} = \bar{\ell}_R \gamma_\mu f \bar{u}_R \gamma^\mu d_R$:

  $m_f \lesssim m_\pi \simeq 140$ MeV to avoid tree-level decay.
  $\rightarrow$ scale of m_f relevant for ν detectors.
- At one loop, $\mathcal{O}_{VR}$ gives $f \rightarrow e^+e^-\nu_e$.
  $\rightarrow$ NP Scale $> 20 - 80$ TeV for $m_f \sim 20 - 80$ MeV .

Constraint on $\mathcal{O}_{VR}$ strong, but weak enough for $\mathcal{O}_{VR}$ to be interesting for ν experiments!

Neutrino Detector Cross-Section

If f comprises all DM,

$$\Phi_{DM} \sim \frac{.3 \text{ GeV}/\text{cm}^3}{m_f} \times 230 \text{ km/s} \sim 10^8 - 10^{10}/\text{cm}^2\text{s}.$$

$\rightarrow$ Would give bump in SK e^+ energy spectrum.

Take $\bar{\nu}_e$ flux limit from Super-K relic supernova $\bar{\nu}_e$ search:

$$\Phi_{\bar{\nu}_e} \lesssim 1.2/\text{cm}^2\text{s for } 20 \text{ MeV} \lesssim E_\nu \lesssim 80 \text{ MeV}$$

(8-10 orders of magnitude smaller!)

Results from Super-K

Ratio of cross-sections ($v =$ Higgs v.e.v.):

$$\frac{\sigma_{\mathcal{O}}(m_f = E_\nu)}{\sigma_{SM}(E_\nu)} = \left(\frac{c}{v_f}\right) \frac{|C_{VR}|^2 v^4}{(8)\Lambda^4}$$

Results (for 20 MeV $< m_f < 80$ MeV):

$$\frac{|C_{VR}|^2}{\Lambda^4} \lesssim \frac{1}{(120\text{ TeV})^4} - \frac{1}{(80\text{ TeV})^4}$$

Limits weaker if f only fraction of DM.

But, very strong limits!

Conclusions

- Nature of DM unknown–should consider other interactions!
- Model-independent analysis of DM interaction $\bar{f}p \to ne^+$in ν exp'ts.
- Inelasticity of interaction allows us to probe different mass range (~ 100 MeV).
- Find one operator (comparatively) unconstrained by DM lifetime for light DM case.
- Reach of ν exp'ts to find light DM huge (~ 100 TeV). May be improved by, e.g., DUSEL.
- Should see if can be applied elsewhere.

ν exp'ts might be telling us more than we think!